

A New Breed of Robot Emerges

by Dawn M. Tilbury and A. Galip Ulsoy, University of Michigan, Ann Arbor, MI

Unmanned ground vehicles (UGVs) are robotic ground vehicles capable of operating in a variety of environments and functioning in place of humans. A typical UGV, the PackBot by iRobot, is shown in Figure 1(left) and consists of a manipulator arm and sensor suite mounted on a mobile (in this case tracked) chassis. Also shown in Figure 1(right) is the OmniTread robot designed to search through rubble. UGVs of various kinds are used to do a variety of dirty, dull, and dangerous tasks, such as vacuuming a room, harvesting crops, carrying heavy loads for long distances, or disabling explosives.

In this article, we document the emergence of UGVs into the economic mainstream, describe the research needed to support their continued evolution, and present examples of current research at the University of Michigan's Ground Robotics Reliability Center (GRRC).

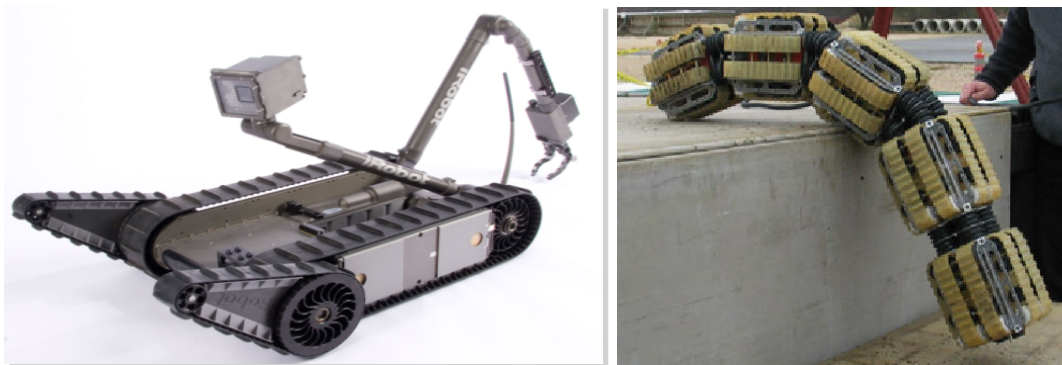


Figure 1. Photo of the PackBot by iRobot (left), and the OmniTread Search and Rescue Robot (right)

What are UGVs

UGVs until recently were seen only in a hobbyist's garage or a university research lab. Today, however, they are being used for a variety of commercial and military purposes. UGVs go places where humans cannot, such as hundreds of meters down oil well pipes, and were used extensively to help rescue workers search the rubble of the World Trade Center. Spirit and Opportunity are examples of UGVs that remotely wandered the Martian surface collecting large amounts of unique data that will be studied for years to come. At the presidential inauguration in 2009, UGVs were driven underneath buses to check for bombs. UGVs have also played a larger and more important role in the armed forces in recent years, with over 8,000 currently deployed by the US Army, compared to only a few hundred less than ten years ago. In Iraq and Afghanistan, various UGVs are used to inspect and disarm potential improvised explosive devices (IEDs), or search caves and buildings. Hundreds of soldiers are alive today because a UGV found or detonated an IED instead of a soldier. They are also used for many other tasks such as surveillance and carrying loads for the soldier. In every one of these examples, UGVs were used to accomplish something that would have been extremely inconvenient, dangerous - or impossible - for a human to do.

No Longer a Hobbyist Activity

The UGV industry is in a situation similar to the automotive industry of a century ago, or to the personal

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computer industry of a few decades ago. It is transitioning from a hobbyist culture and emerging as a major new industry, as it is called upon to meet important societal needs. This was highlighted by Bill Gates in the December 2006 *Scientific American* article "A Robot in Every Home" in which he stated "... the robotics industry ... is developing much the same way as the computer business did 30 years ago." The Office of Science and Technology Policy (OSTP), in a post by T. Kalil and S. Kota on the OSTP website on 9/15/2010, has identified robotics as a top research and development priority for the nation: "Robotics is an important technology because of its potential to advance national needs such as homeland security, defense, medicine, healthcare, space exploration, environmental monitoring and remediation, transportation, advanced manufacturing, logistics, services, and agriculture. Robotics is also nearing a tipping point in terms of its usefulness and versatility as technologies such as software, chips, and computer vision continue to improve." In a New York Times article from 9/14/2010 the Austin, Texas futurist George Friedman is quoted as saying that robotics, not alternative energy or other emerging technologies, is the technology that is going to help the State of Michigan's economy to boom again after its loss of hundreds of thousands of manufacturing jobs in the ailing automotive industry. These are all indicators that the UGV industry is well on its way to entering the economic mainstream.

Industrial robots have been around for decades, efficiently performing tasks such as spray painting, welding and assembly in manufacturing plants, and continue to grow in numbers. However, a new generation of robots, as exemplified by UGVs, are quite different from their industrial robot cousins, is now emerging. Industrial robots are pre-programmed to repetitively perform routine tasks with precision and reliability. They operate in a well-known and structured environment, and have little or no interaction with humans once they are programmed and turned on. UGVs, on the other hand, perform a variety of tasks and encounter many diverse operating environments, from carpeted floors and stairs in buildings, to hot and sandy conditions in the deserts of Iraq. Their interactions with human operators, or with human or robot partners, can be quite varied and complex. These all contribute to reduced reliability, as illustrated in Fig.2.

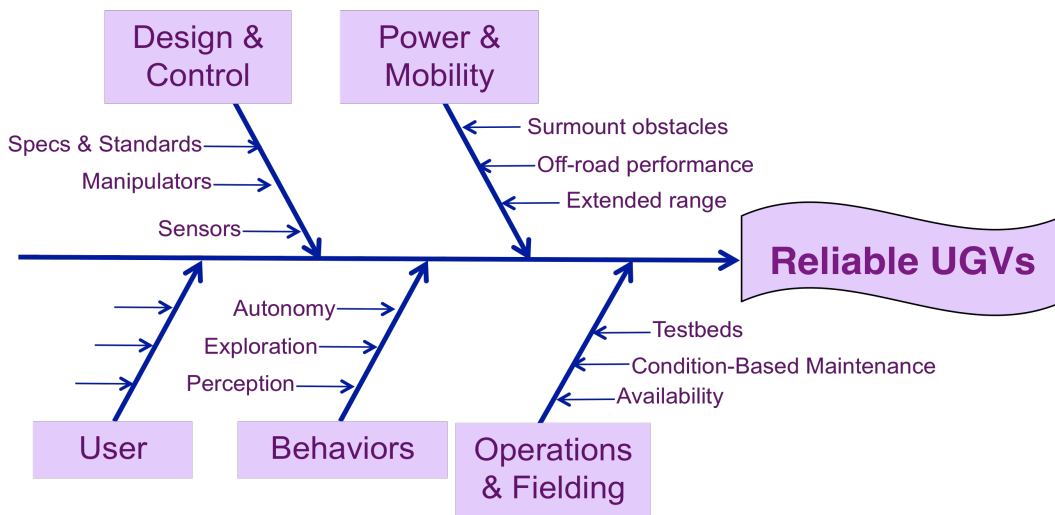


Figure 2 Fishbone Diagram, Showing Major Contributors to UGV Reliability

Consequently, because the UGV industry is very young with many new technologies, because UGVs are difficult for humans to interact with, and because UGVs operate in uncertain environments, they currently suffer from a number of reliability issues and break down frequently. Recent studies by J. Carlson, R. Murphy and co-workers for search and rescue UGVs show that the mean time between failures is typically between 6 and 20 hours. We have heard similar reports in personal communications during a visit to the US Army Joint Robotics Repair and Fielding facility at Selfridge Air National Guard base. Consequently, the reliable operation of UGVs is an important current concern, just as the reliable operation of the early personal computers was in the 1970's, or the reliable operation of early automobiles was at the start of the 20th century.

From Tele-operation to Autonomy

Currently most UGVs are remote controlled, or tele-operated, and this significantly limits their capabilities and the missions they can successfully undertake. Their effective use requires the dedicated attention of skilled operators. Typically, joystick-type interfaces are used by trained operators to move the platform, as well as to separately control the motion of the manipulator arm and the sensors. For some demanding tasks, multiple operators may be needed to control a single UGV, and in combat operations, extra personnel may be needed to guard a robot operator whose attention is focused on the small screen. Operators may only have feedback about the UGV operation from limited sensors on board the UGVs, or through line-of-sight visual contact. Such restrictions limit the complexity of the missions that can be undertaken, and also limit the distances at which the UGVs can be operated.

Inevitably, UGVs will become increasingly autonomous, moving gradually from tele-operation to limited supervised autonomy to eventually fully autonomous operations. DARPA has sponsored the DARPA Grand Challenge and DARPA Urban Challenge competitions, to encourage the development of UGVs, with increased levels of autonomy. Teams of autonomous ground robots demonstrated their reconnaissance and surveillance abilities in the MAGIC competition, co-sponsored by the US and Australian defense departments. In a May 2010 report, entitled *Technology Horizons*, by the Chief Scientist of the US Air Force, the importance of autonomy was clearly emphasized:

“The single greatest theme to emerge from “Technology Horizons” is ... far greater use of autonomous systems ... Increased use of autonomy -- not only in the number of systems and processes to which autonomous control and reasoning can be applied but especially in the degree of autonomy that is reflected in these --can provide ... potentially enormous increases in its capabilities, and if implemented correctly can do so in ways that enable manpower efficiencies and cost reductions.”

While autonomy enables more complex missions, and operations over larger distances, it also requires more reliable operations of the UGVs themselves. While cars, for example, are typically designed for a 100,000 mile life, current UGV design goals are a mean-time-between-failure (MTBF) of 100 hours, and most actually achieve MTBF of about 20 hours or less. The autonomous UGVs of the future, to which increasingly complex and important missions will be entrusted, need to be significantly more reliable.

Research Needs for UGVs

Although increasing numbers of UGVs are being deployed every day, there remain many important research questions to be investigated. As noted above, UGVs must become increasingly autonomous. UGVs must be enabled to make critical tactical decisions instead of only following preprogrammed actions, or relying on teleoperation. For this, autonomous controls will be required, so that they can operate either independently or as part of a mixed team of humans and robots. UGVs must be able to operate in close proximity to humans, safely even at high speeds. Improved methods for teleoperation and shared human/robot control are needed. Better sensors – and sensor processing – can improve situational awareness for both the robot and its operator. Since UGVs must operate in challenging and unknown environments, mobility is important. Mission durations are currently limited by battery life. Finally, both design and manufacturing of UGVs must improve to achieve the reliability required for future generations.

Many universities and other research organizations around the world are engaged in research related to UGVs. For example, The University of Michigan's Ground Robotics Reliability Center (see <http://grrc.engin.umich.edu>), funded in part by the Joint Center for Robotics at the Department of Defense, has grouped the research needs described above under the umbrella of *reliable operations*, and is working on a number of research projects to address these needs. Some of these research projects will be described here.

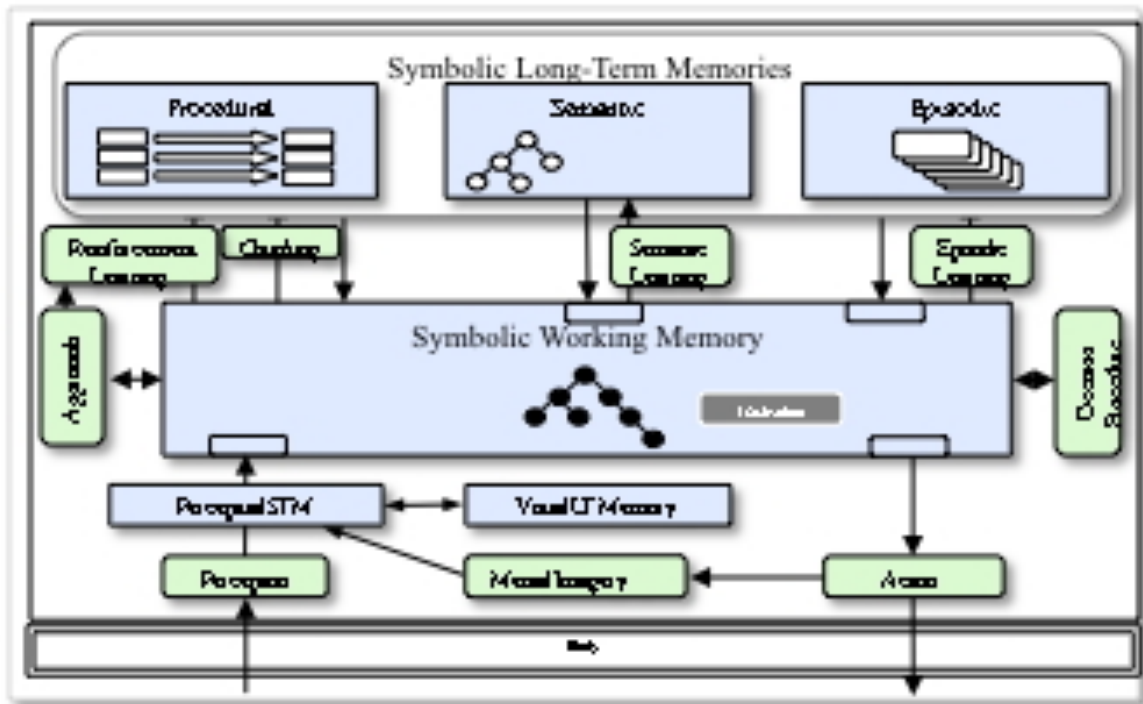


Figure 3. The Soar Architecture for Artificial Intelligence

Reliable Behavior through Instruction

Techniques that can dynamically extend the behavior of unmanned robotic systems, while ensuring the reliability of the new and modified behaviors, will increase the level of autonomy of UGVs. This approach focuses on interactive instruction, in which a human guides the robot in new missions, tactics, and skills, verifying the correctness of the robot's behavior during performance or rehearsal. The approach is situated — the human gives instructions while the robot is performing a task, and so the instruction is grounded in the real world, thereby eliminating many forms of ambiguity. The approach is interactive — the robot can ask for help when it needs it, and the human can correct any errors that are noticed. Trust is built and established through confirmation and explanation — the robot can explain what it is doing in a certain situation. Prof. John Laird and his coworkers are implementing this research using the Soar cognitive architecture as shown in Figure 3, an open source core infrastructure for decision-making, planning, and complex doctrine execution.

Autonomous Exploration and Inventory of Human-Filled Spaces

In order to operate reliably in diverse environments, robots must be able to sense and interpret their surroundings. Prof. Ed Olson and his coworkers are developing a robotic system that is capable of autonomously exploring a previously unknown area, producing an inventory of that space. By inventory, we mean that the robot will build a metrically accurate map that is annotated with other tactically important information. For example, the robot will report the location and activities of humans within that space, along with the location of other features of interest. The identification of these objects could eventually be combined with the exploration strategy: tracked humans could be pursued (in order to aid apprehension of suspects, for example) or avoided (to maximize the stealth of the system). Both video and range finding sensors (e.g., LIDAR) have been used with some success in map-building. In our work, we are combining the best attributes of both types of sensors in order to improve the feature recognition and understanding of three-dimensional space. LIDAR has been recognized as good for capturing geometry but with poor appearance data, while cameras give rich appearance data but poor geometry. We use both sensors, rigidly

attached to each other to facilitate coordinate transformations. By combining the two sensors' data, improved object segmentation is achieved, as shown in Figure 4. These capabilities have been deployed in a team of robots that won the 2010 MAGIC competition.



Figure 4. The camera scene is shown in the center. Different methods for segmentation achieve varying results; our method combines camera and range data (shown in the lower left) and is the most successful.

Integrated Power Systems for Improved Mobility of Ground Robotics

Energy and power are critical for reliable operation of mobile robots. Prof. Huei Peng and his coworkers are considering UGVs requiring total power levels of several hundred watts to several kilowatts, and have the size of a backpack. Figure 5 shows the power requirements and stored energy available for a number of different robots and other powered devices. The mission durations are indicated by diagonal lines. As shown in the figure, currently-available portable UGVs (numbers 5 and 6 in the figure) have mission durations of just over an hour; our goal is to increase that to 8-10 hours. We are developing a systematic process for the design and control of energy systems for ground robots, thereby improving their reliability of their operations.

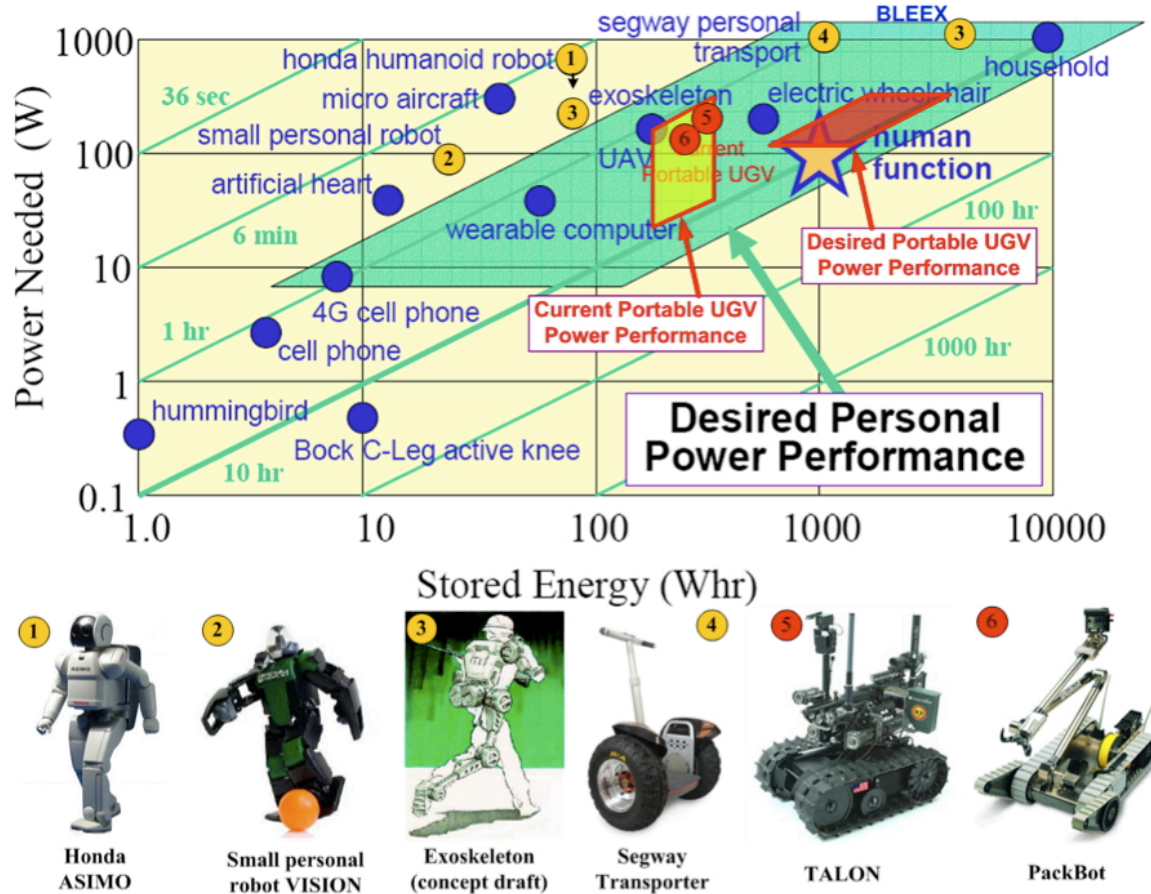


Figure 5. Power requirements and energy storage, with operating durations shown as diagonal lines.

Moving Obstacle Avoidance with Sensor Uncertainty

The problem of avoiding moving obstacles with uncertain sensor data has not been adequately addressed; solving this problem is the focus of this project by Prof. Galip Ulsoy and his coworkers. In addition to assuming that the sensor data is uncertain, we also assume that the environment is unknown. In our approach, the robot's environment is decomposed into a grid of individual cells, each corresponding to a velocity of the mobile robot. For each moving obstacle, a *velocity obstacle* is the set of robot velocities that will lead to a collision with the robot. The velocity occupancy space combines the velocity obstacles (including the sensor noise) and the goal position of the robot in a weighted average for each velocity grid cell, as shown in Figure 6. Different types of obstacles (such as pedestrians or cars) can have different weights. At each time step, the robot selects the reachable velocity with the largest combined cost. Using hand-tuned weights for the positive (attractive) potential of the goal and the negative (repulsive) potential of the obstacles, good simulation results were achieved. We are currently integrating sensors onto a UGV for validating the results experimentally.

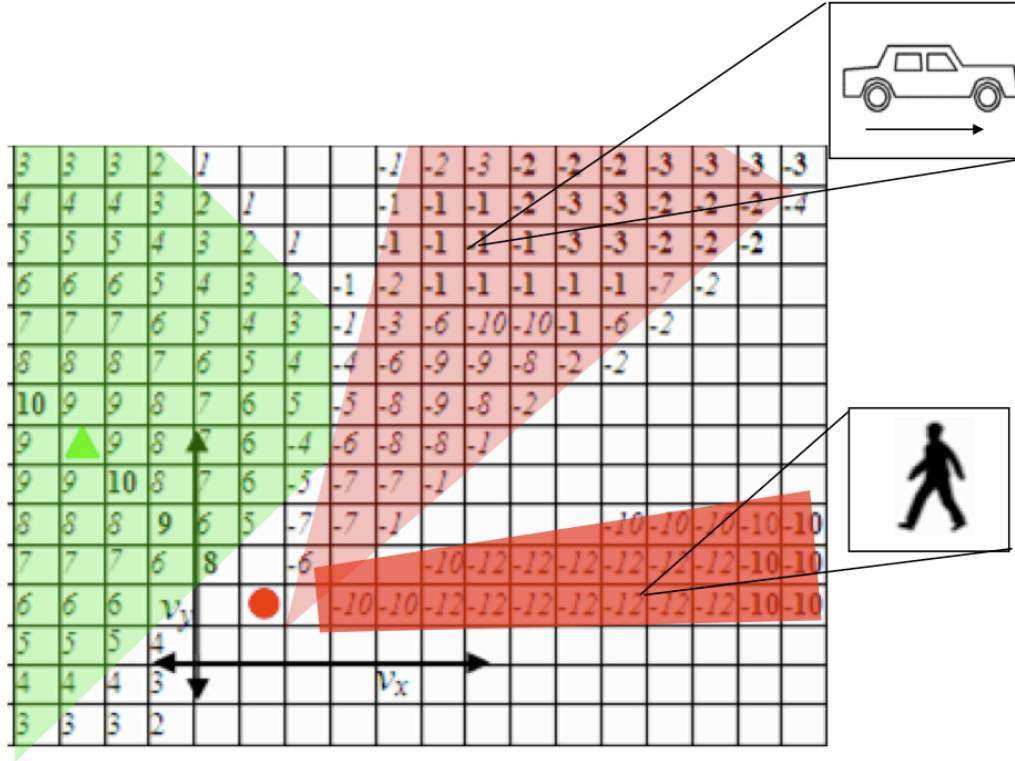


Figure 6. Velocity occupancy space, showing the positive (green) costs for velocities that approach the goal and negative (red) costs for velocities that approach the (moving) obstacles.

Indoor Position Tracking for UGVs

When UGVs are teleoperated, it can be difficult for the operator to keep track of them while they are exploring a building. GPS is not available inside buildings, and the limited information available from onboard sensors can be confusing. Even in a familiar building, operators often get disoriented, and look for landmarks to figure out where the robot is. To improve the reliability of locating UGVs in indoor environments, Prof. Johann Borenstein and his coworkers are developing an extremely accurate position tracking system for small, tele-operated robots. This Indoor Position Tracking (IPT) system produces accurate real-time trajectories of the robot on the operator's screen, providing accurate position and heading information. In addition, if the robot becomes incapacitated or if communication breaks down, the last known position of the robot is immediately evident from the trajectory plot. This allows for the quick extraction of the robot with minimal exposure for the rescuers. The IPT system is based on low-cost gyros and inertial measurement units, which are used for dead reckoning. Traditionally, the drift inherent in such sensors has rendered the measurements useless after a short time. However, we have developed a heuristic method for drift elimination. A path through a building is shown in Figure 7. On the left the path is computed using direct integration of the gyro; on the right, our drift elimination algorithm is applied to the same gyro data to compute the path. There is a small position error between the start and stop positions, but the heading error is completely eliminated. Applications of this and related technology include leader-follower scenarios, and methods to assist operators of tele-operated UGVs with their navigation. These are being demonstrated at the Robotics Rodeo in Fort Benning, GA.

The GRRC has also developed a robotics testbed that includes a Packbot and several other small robots as shown in Figure 8. The robots are interfaced with a variety of different sensors, and with a standard interface software, i.e., the University Research Controller (URC), that will enable the different research projects to test and validate their results using a common interface regardless of hardware and software differences in the UGVs. The URC not only enables researchers to implement the new results of their

research on a variety of platforms, but also protects the proprietary aspects of commercial UGV platforms in the testbed, thus, supporting technology transfer and commercialization of the research.

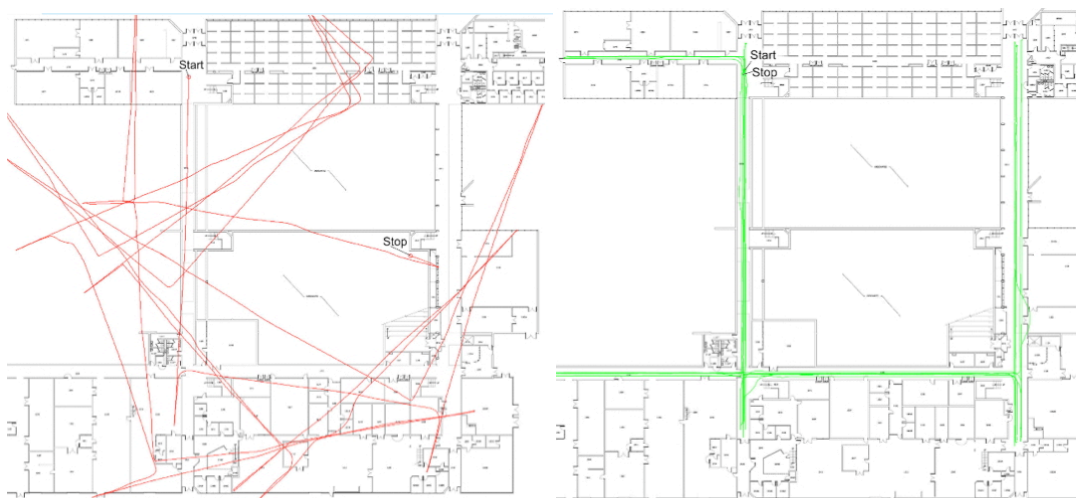


Figure 7. Trajectory computed with gyro odometry data, overlaid on the building plan. Red (left) is conventional integration for dead-reckoning; green (right) is the same data with our drift elimination algorithm applied.

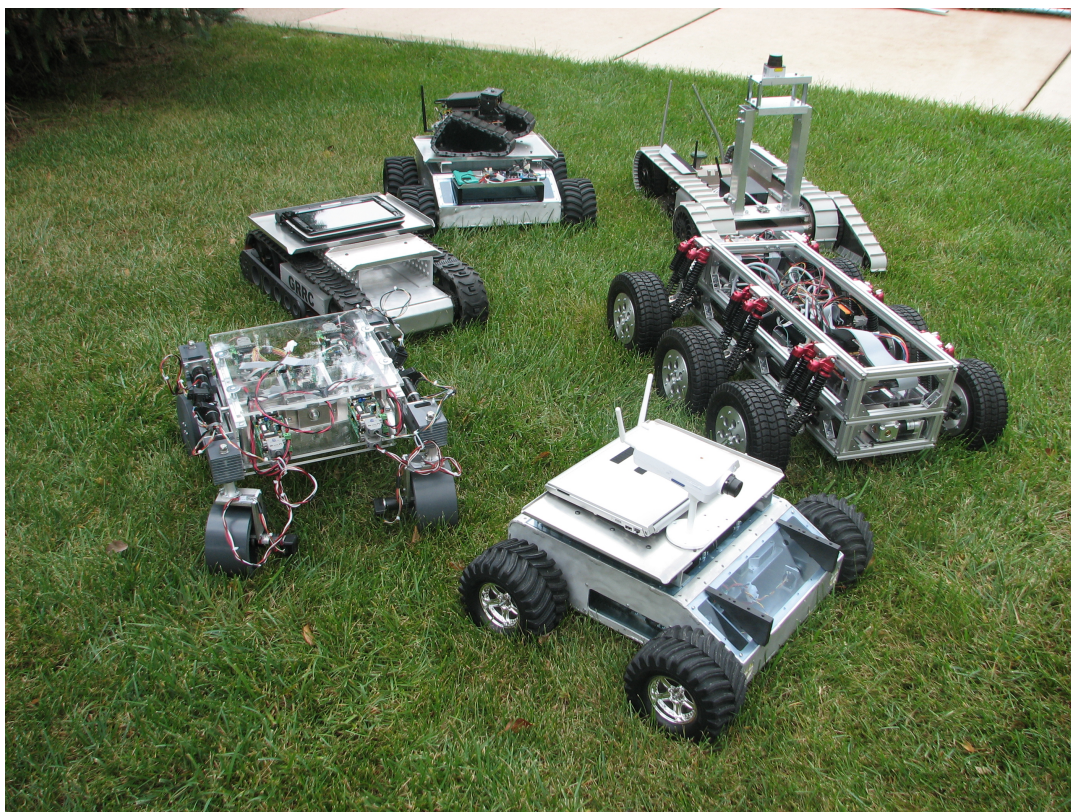


Figure 8. A Fleet of UGVs at the GRRC Testbed

Concluding Remarks

A new breed of robot, able to replace humans in performing a variety of difficult and unpleasant tasks, is emerging from the hobbyist's garage and entering the economic mainstream. The unmanned ground vehicle (UGV) industry is in many ways at a similar stage of development as the personal computer industry was in the mid 1970's. There is a demand for the increasingly autonomous and increasingly reliable operations of UGVs, and very active research programs around the world to support those needs.

We have highlighted a few examples of such research at the GRRC at the University of Michigan, including instruction-based programming, map-building, energy management for hybrid powertrains, safe operation around humans, and UGV position tracking. Many other research projects at the GRRC, including adjustable autonomy, enhanced reliability through design optimization, control reconfiguration, and augmented reality user interfaces, are also contributing to the reliable operations of UGVs. With such ongoing research efforts worldwide, a new breed of autonomous and mobile robot will indeed emerge into the economic mainstream.

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